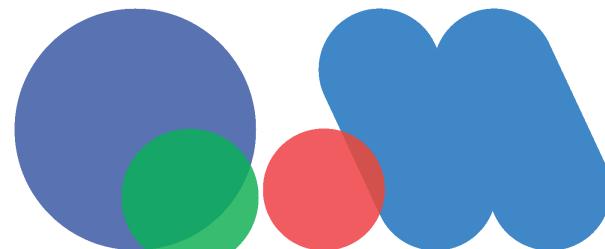


# **PHENIX results on fluctuations and Bose-Einstein correlations in Au+Au collisions from the RHIC Beam Energy Scan**

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# OUTLINE

⌘ **Introduction**

⌘ **Net-charge fluctuations Results of PHENIX**

⌘ **BE Correlation Measurement Results of PHENIX**

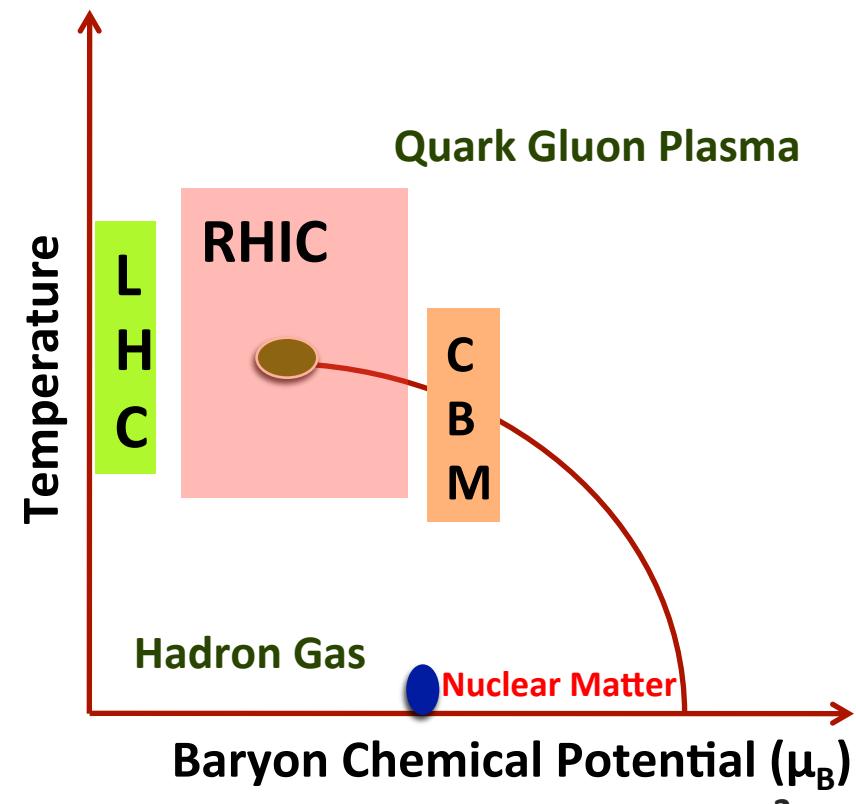
⌘ **Conclusions**

# BES Motivation: CEP

- \* The temperature driven transition at zero  $\mu_B$  indicate a rapid crossover from the hadronic phase to the QGP phase for realistic u, d and s quark masses.
- \* The  $\mu_B$  driven transition at finite T is a first order phase transition.
- \* A first order line originating at zero T must end somewhere in the midst of the phase diagram where the phase transition is a crossover

*This end point of a first order phase transition line is a critical end point (CEP)*

Limited theoretical guidance,  
need data!!



# BES: Overview

Energy (GeV)	7.7	11.5 STAR only	14.5	19.6	27	39	62.4	200
Run-Year	2010	2010	2014	2011	2011	2010	2010	2010
Integrated Luminosity	1.75 $\mu\text{b}^{-1}$	7.82 $\mu\text{b}^{-1}$	72.3 $\text{nb}^{-1}$	15.7 $\mu\text{b}^{-1}$	32.7 $\mu\text{b}^{-1}$	107 $\mu\text{b}^{-1}$	281 $\mu\text{b}^{-1}$	5.01 $\text{nb}^{-1}$

This Talk will focus:

- Net-charge Fluctuations [[arXiv:1506.07834](#)]  
Increased fluctuations in the vicinity of CEP
- Two-pion Interferometry Measurements [[arXiv:1410.2559](#)]  
Evidence of 1<sup>st</sup> order phase transition or softening of equation of state

# Fluctuations: Theory to Experimental observable are performed using cumulants

- Cumulants of fluctuations of conserved quantities are related to thermodynamic susceptibilities (*Lattice QCD and Hadron Resonance Gas (HRG) model*)

❖ 1<sup>st</sup> moment:

mean  $\mu = \langle x \rangle$

❖ 2<sup>nd</sup> cumulant:

variance  $\kappa_2 = \sigma^2 = \langle (x - \mu)^2 \rangle$

❖ 3<sup>rd</sup> cumulant:  $\kappa_3 = \mu_3 = \langle (x - \mu)^3 \rangle$

❖ 3<sup>rd</sup> standardized cumulant:

skewness =  $S = \kappa_3 / \kappa_2^{3/2} = \langle (x - \mu)^3 \rangle / \sigma^3$

❖ 4<sup>th</sup> cumulant:  $\kappa_4 = \langle (x - \mu)^4 \rangle - 3\kappa_2^2$

❖ 4<sup>th</sup> standardized cumulant:

kurtosis =  $K = \kappa_4 / \kappa_2^2 = \{ \langle (x - \mu)^4 \rangle / \sigma^4 \} - 3$

$$\frac{\kappa_2}{\kappa_1} = \frac{\sigma^2}{\mu} = \frac{\chi_2}{\chi_1}$$

$$\frac{\kappa_4}{\kappa_2} = K\sigma^2 = \frac{\chi_4}{\chi_2}$$

$$\frac{\kappa_3}{\kappa_2} = S\sigma = \frac{\chi_3}{\chi_2}$$

Calculate moments from the event-by-event net charge distribution  $\Delta N = N^+ - N^-$

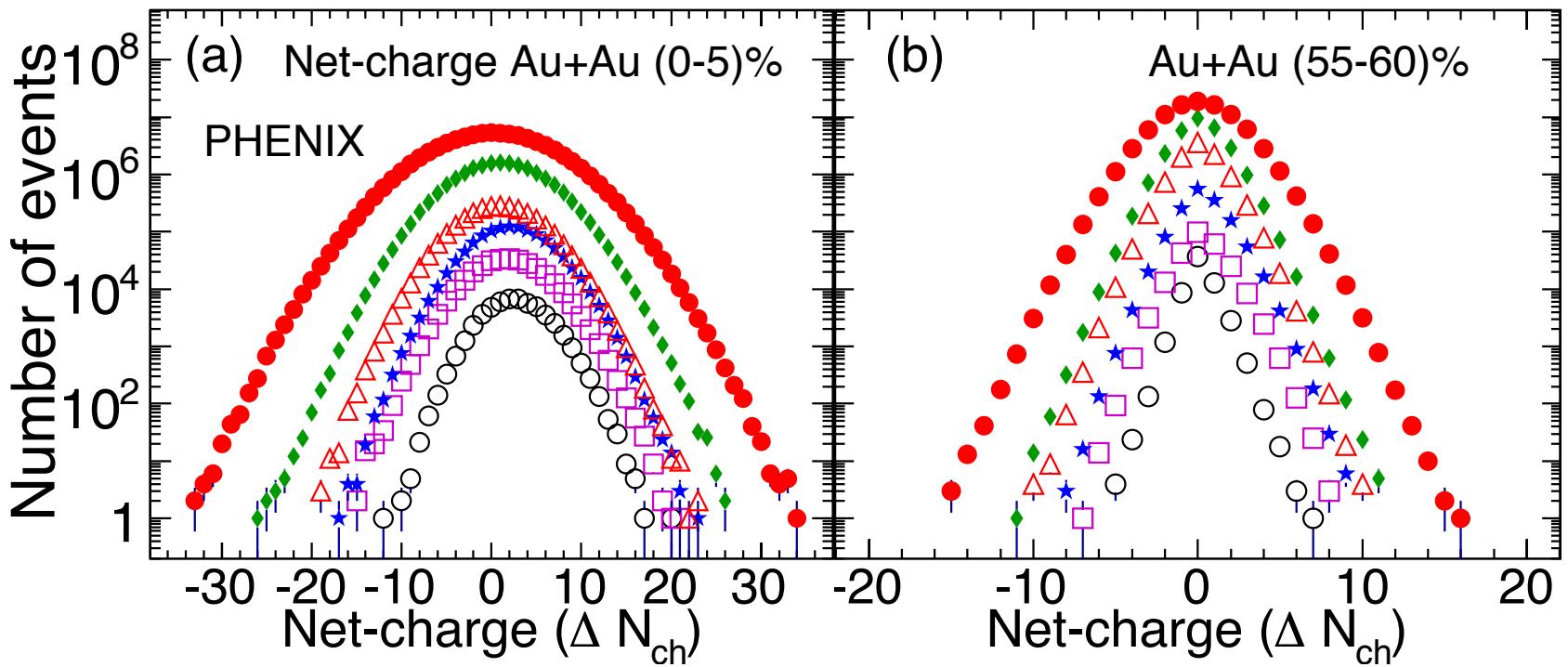


Cumulant ratios are  
Independent of Volume

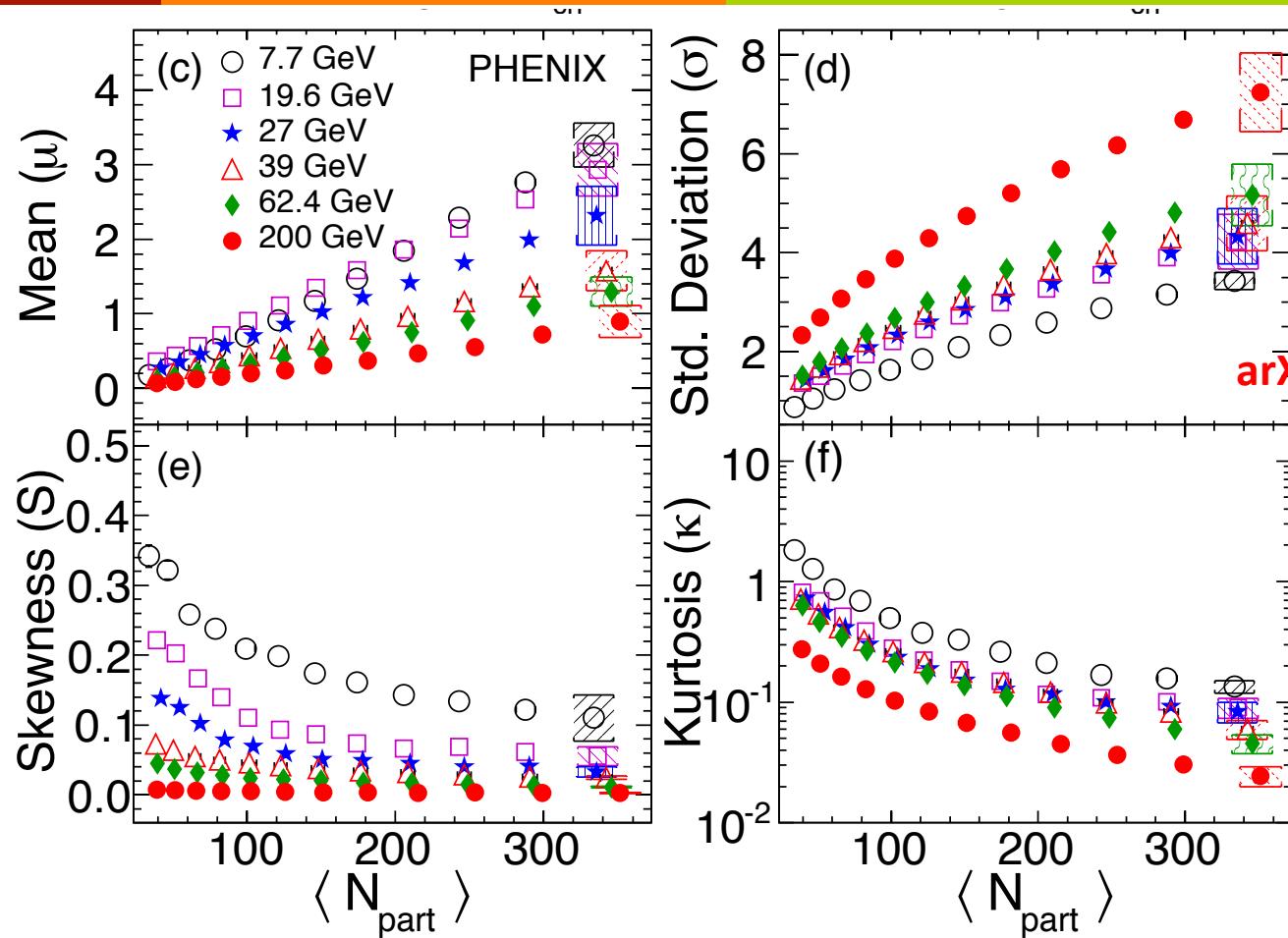
# Net-charge ( $N_{ch}$ ) Distributions

Uncorrected net-charge  
( $N_{ch}$ ) distributions

arXiv:1506.07834



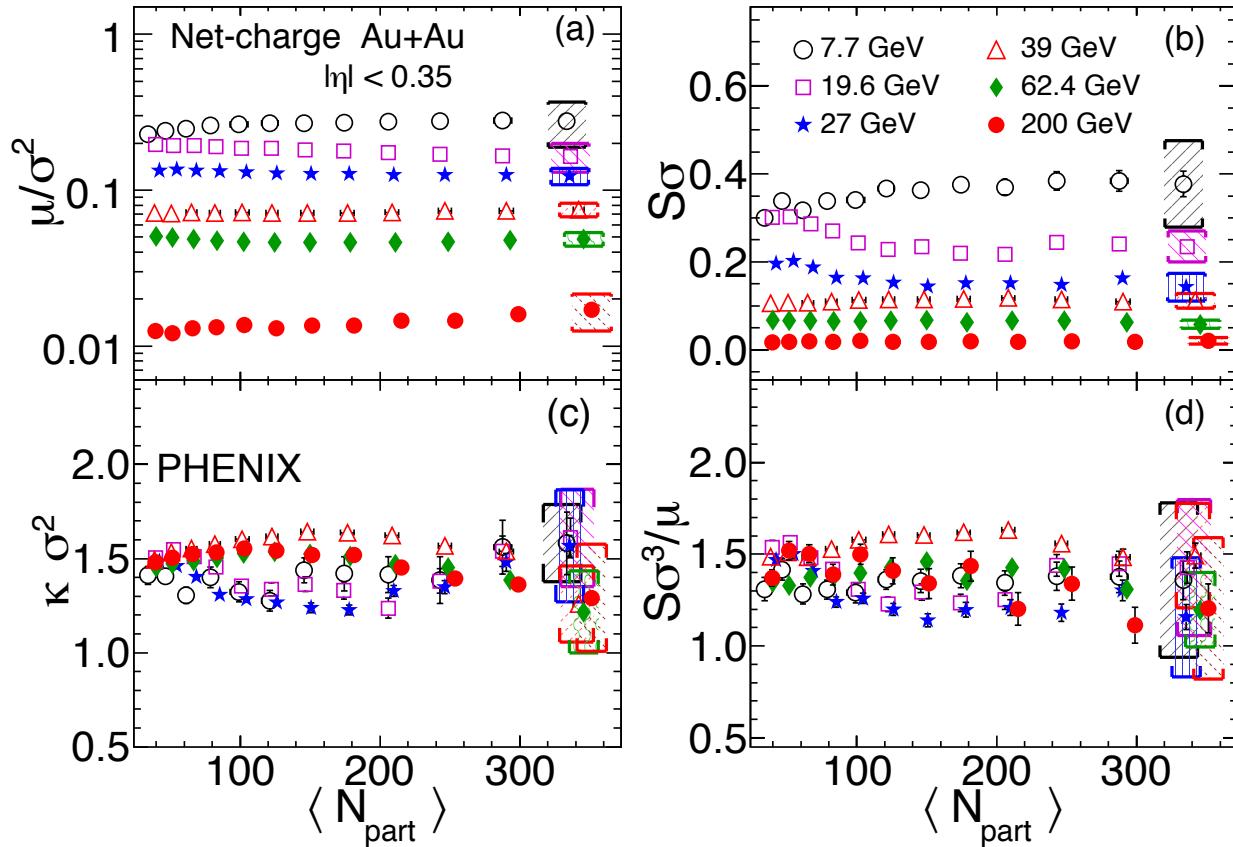
# Efficiency Corrected Cumulants



arXiv:1506.07834

Reconstruction Efficiency corrected cumulants\*\* of net-charge distributions as a function of  $\langle N_{\text{part}} \rangle$

# $N_{\text{part}}$ Dependence of Cumulant Ratio



arXiv:1506.07834

The ratios of the corrected cumulants are weakly dependent on  $\langle N_{\text{part}} \rangle$  for each collision energies within the systematic uncertainties.

# Cumulant Ratios vs $\sqrt{s_{NN}}$

- Data matches with Negative Binomial Expectations

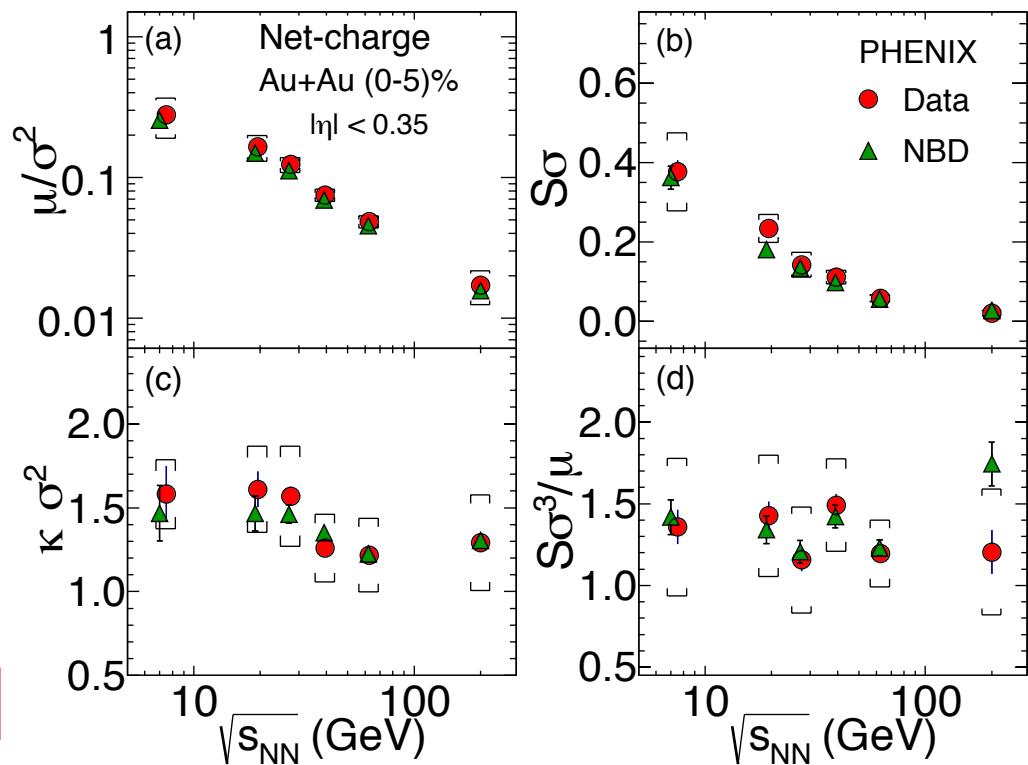
(Green triangles are from cumulant theorem for difference of two Negative Binomial Distributions)

- $\mu/\sigma^2$  and  $S\sigma$  decrease from lower to higher collision energies

- $\kappa\sigma^2$  and  $S\sigma^3/\mu$  values are constant as a function of  $\sqrt{s_{NN}}$  within systematic uncertainties.

See also poster by M. J. Tannenbaum

arXiv:1506.07834



PHENIX data are in agreement with previous STAR data

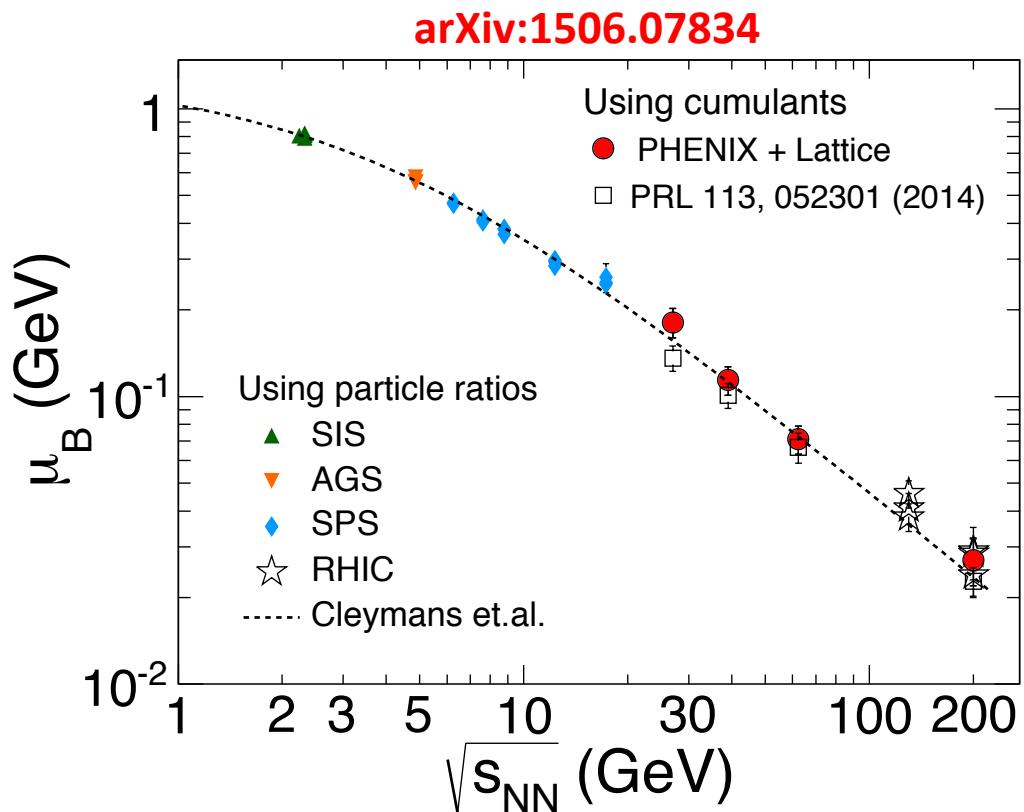
BUT

are more precise determination of the higher cumulant ratios

# Experimental Data + Lattice = Physical Quantities

Net-charge cumulants data + Lattice QCD calculation gives both freeze-out  $T_f$  + Baryon Chemical Potential  $\mu_B$  **without particle identification!!**

$\sqrt{s_{NN}}$ (GeV)	$T_f$ (MeV)	$\mu_B$ (MeV)	$\mu_B$ (MeV)**
27	$164 \pm 6$	$181 \pm 21$	$136 \pm 13.8$
39	$158 \pm 5$	$114 \pm 13$	$101 \pm 10$
62.4	$163 \pm 5$	$71 \pm 8$	$66.6 \pm 7.9$
200	$163 \pm 8$	$27 \pm 5$	$22.8 \pm 2.6$



\*\*S. Borsanyi et al., Phys. Rev. Lett. 113, 052301 (2014) assuming  $140 < T_f < 150$  MeV

Agreement with thermal-statistical model

J. Cleymans, Phys. Rev. C 73, 034905 (2006)

# Expansion Dynamics: Theory to Experimental observable

HBT radii = initial size + size due to expansion + effects of position-momentum correlations

HBT radii to actual physical observables

$$R_{side}^2 = \frac{R_{geo}^2}{1 + \frac{m_T}{T} \beta_T^2}$$

$$R_{out}^2 = \frac{R_{geo}^2}{1 + \frac{m_T}{T} \beta_T^2} + \beta_T^2 (\Delta\tau)^2$$

$$R_{long}^2 = \tau^2 \frac{T}{m_T} \frac{K_2}{K_1}$$

$$R_{out}^2 - R_{side}^2 \propto \Delta\tau$$

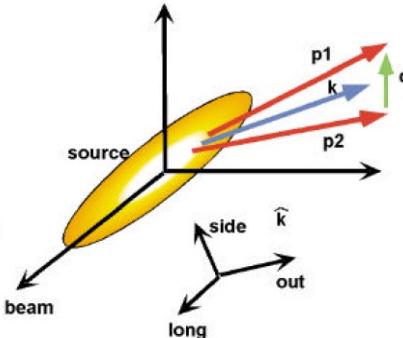
 Sensitive to emission duration

 Extended Emission duration

 1<sup>st</sup> Order phase transition

 Medium Life Time

# Two-pion correlation functions



Space-time information is extracted by fitting  $C_2(q_i)$  with:

$$C_2(q_s, q_o, q_l) = 1 + \lambda \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_o^2 q_s^2)$$

$q_{\text{side}} \rightarrow \perp$  to the beam direction  $\rightarrow R_{\text{side}}$

$q_{\text{out}} \rightarrow \parallel$  to the average transverse

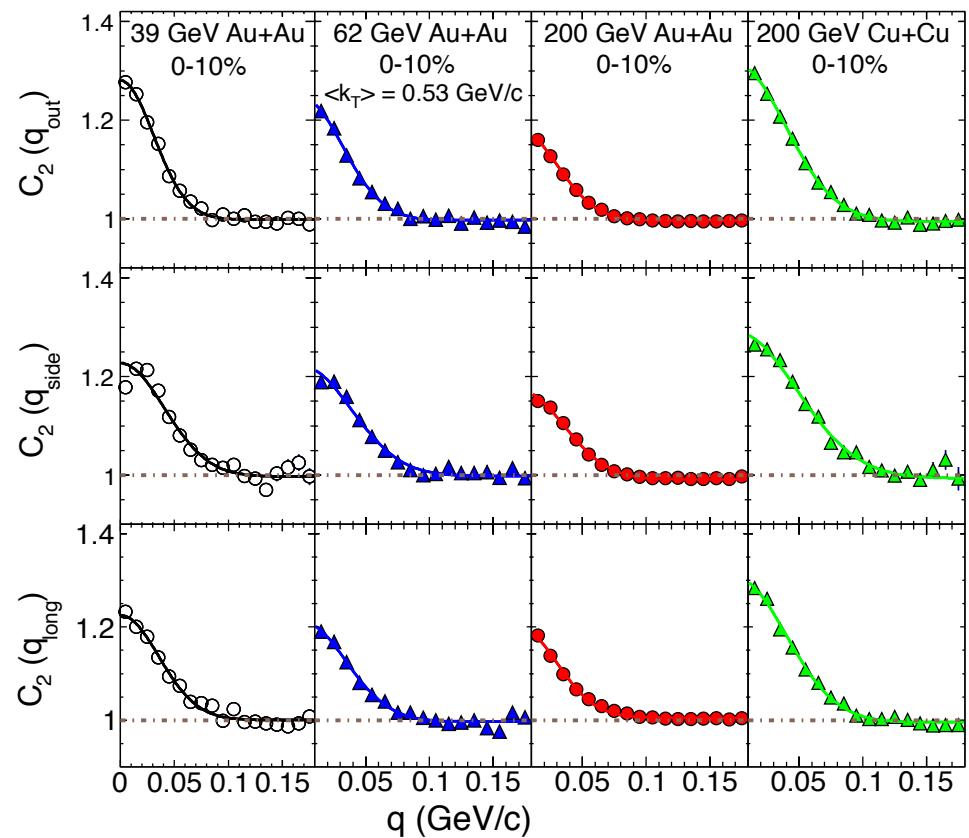
momentum of pair  $\rightarrow R_{\text{out}}$

$q_{\text{long}} \rightarrow$  along beam direction  $\rightarrow R_{\text{long}}$

(Coulomb Corrected)

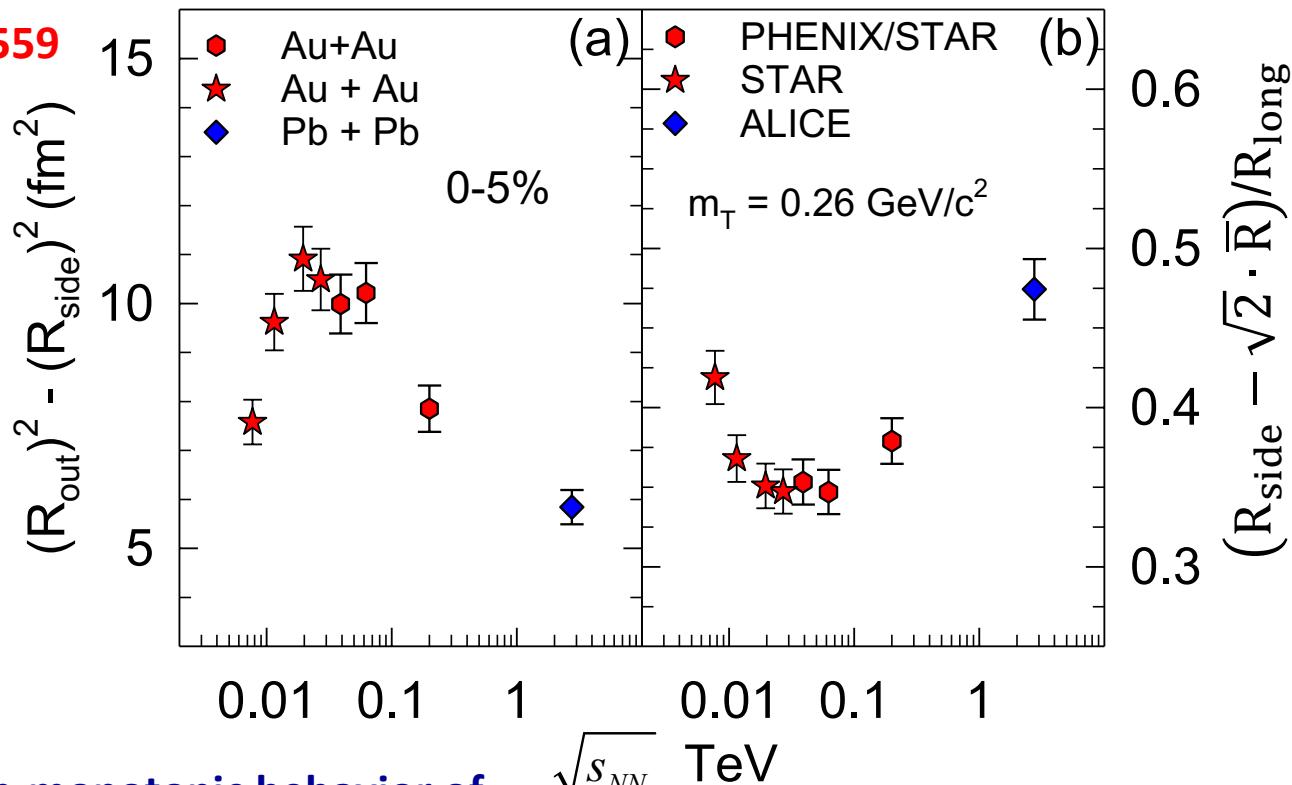
and in LCMS ( $p_{1z} + p_{2z} = 0$ )

arXiv:1410.2559



# Expansion dynamics in HBT

arXiv:1410.2559



- Non-monotonic behavior of

$$R_{\text{out}}^2 - R_{\text{side}}^2$$

(proportional to emission duration  $\Delta\tau$ )

$$(R_{\text{side}} - \sqrt{2}R)/R_{\text{long}}$$

(related to medium expansion velocity).

Softening of equation of state near the CEP?

# Conclusions

$K\sigma^2$  and  $S\sigma^3/\mu$  values remain constant over all collision energies within uncertainties  
- No clear sign of CEP

Higher moments measurements together with the lattice calculations  
-Extract the freeze-out temperature  $T_f$  and baryon chemical potential  $\mu_B$

Non-monotonic behavior observed in HBT measurements proportional to system emission duration and expansion speed over narrow energy range ( $\sim 27$ - $50$  GeV)  
-Could be indicative of softening of equation of state/onset of deconfinement